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ADDITIONAL DESIGN CONSIDERATIONS FOR BOLTED CONNECTIONS

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ABSTRACT

A multi-year study was conducted at the University of Missouri-Rolla which focused on such topics as deformation characteristics of bearing type connections; strength of bearing and tensile type failure modes of flat sheet connections; tensile strength of staggered bolt patterns in flat sheet connections; and tensile strength of bolted connections for angle and channel sections. The intent of this research was to verify the present design approach for bolted connections and to expand the design methodology to include additional limit states, in particular the effect of deformation of the bolt hole and the influence of shear lag in angle and channel sections. This paper summarizes the scope and findings of recent UMR research as it pertains to the topics of bolt hole deformation and shear lag.

INTRODUCTION

An experimental and analytical study was initiated at the University of Missouri-Rolla (UMR) in 1993 to expand the knowledge and understanding pertaining to the behavior of cold-formed steel bolted connections. The details of this research project are reported in two research reports (Carril et al., 1994; Holcomb et al., 1995). This paper presents a summary of the findings of this two-year research effort, as well as proposes appropriate design recommendations.

Previous research, which serves as the foundation for the present design specifications (Specification, 1986; Load, 1991), has focused on the ultimate strength behavior of flat sheet connections with symmetrical bolt patterns. The research addressed by the most recent UMR study explored such topics as deformation characteristics of bearing type connections; strength of bearing and tensile type failure modes of flat sheet connections; tensile strength of staggered bolt patterns in flat sheet connections; and tensile strength of bolted connections for angle and channel sections.

This paper presents the salient findings of the UMR research pertaining to deformation characteristics of bearing type connections and the tensile strength of bolted connections for angle and channel sections. It also reports on the development of design recommendations that were structured to be consistent with the design practices of hot-rolled steel construction (Specification, 1989; Load, 1993).

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FIRST SUMMARY REPORT

The intent of this phase of the research project was to compare the present AISI and AISC Specifications for the nominal bearing and tensile capacities, and also to develop appropriate bolt deformation design criteria for bolted connections.

Prior to engaging in the experimental phase of this study, a comprehensive review of available literature was performed and is summarized by Carril (1994). The literature represented 719 bolted connection tests which were conducted by an array of researchers in the United States. The connection test data represented flat sheet specimens subjected to either single or double shear and either with or without washers, as summarized in Table 1. Carril's evaluation compared the tested failure load to the computed failure load for the appropriate failure mode. Five computation techniques were explored: AISI Specification (1986), AISC Specification (1989), ECCS Recommendations (1987), British Standard (1987), and Canadian Standard (1989). Based on the statistical findings, the following summarizes the more significant observations that were made:
(1) The AISI Specification is adequate for tension failure in bolted connections using a single bolt. For connections with multiple bolts, the Specification is slightly conservative.
(2) The AISI Specification is slightly unconservative for single bolt connections that failed a combined failure mode of bearing and tearing due to excessive bolt rotation and dishing of the connected parts.
(3) In general, the European design formulas were found to be more conservative than the AISI Specification.
The findings of this effort aided in defining the experimental phase of the research.

Experimental studies were performed to investigate the tensile capacity, the bearing capacity and the interaction of tension and bearing capacities of flat sheet cold-formed steel bolted connections. The effect of bolt hole deformation on the bearing capacity of bolted connections was also investigated. In the experimental investigation, single-shear, flat sheet connections having either single or multiple bolt configurations were studied. The specimens were designed for the following parameters: (1) nominal sheet thickness: 1.02 mm (0.04 in.), 1.78 mm (0.07 in.) and 3.05 mm (0.12 in.); (2) ratios of d/s: 0.12, 0.15, and 0.31; (3) 12.7 mm (1/2 in.) diameter A325T bolts; (4) bolt pattern configurations, as shown in Fig. 1; and (5) with and without washers.

Tensile coupon tests were conducted to obtain the mechanical properties of the steel sheets. Table 2 lists the measured thicknesses and mechanical properties of the sheet steel used in this phase of the investigation.

The experimental stage of this research consisted of 75 tests of two identical flat sheet test specimens bolted together (Fig. 2). In addition to determining the ultimate load capacity of each test specimen, the load deformation characteristics were also defined. Using an LVDT, deformation performance of each bolted connection was continuously measured during the loading process (Fig. 3).

Using the load-deformation history, a service load was defined for each test specimen. The service load was based on a deformation limit of 6.36 mm (0.25 in.). This limit was chosen to be consistent with the deformation limit adopted by both the Research Council on Structural Connections (1988), and the AISC specifications (Specification, 1989; Load, 1993). A recommendation is presented herein for defining the design service load.

For the test specimens that failed in bearing, the AISI specifications (Specification, 1986; Load, 1991) were shown to be good predictors of the ultimate strength. The AISC specification (Load, 1993) was found to be less accurate a predictor of the ultimate strength.

Both the AISI and AISC specifications were deemed to be good predictors of the limit state of fracture in the net section for the test specimens in this experimental study.

SECOND SUMMARY REPORT

The research summarized in the Second Summary Report (Holcomb et al., 1995) addressed the tensile capacity and bearing capacity of bolted connections of flat sheet, angle, and channel cold-formed steel members. The specimens were designed for the following parameters: (1) nominal sheet thickness: 1.02 mm (0.04 in.) and 3.05 mm (0.12 in.); (2) ratios of d/s: 0.09 and 0.31; (3) 12.7 mm (1/2 in.) diameter A325T bolts; (4) bolt pattern configurations, as shown in Figs. 4 and 5; and (5) with and without washers. Table 2 lists the material properties for the sheet thicknesses used to form the angle and channel cross sections.

Both angle and channel sections were subjected to a tensile load parallel to their longitudinal axis. Fifty-four angle and fifty-one channel specimens were load tested. For those specimens that exhibited a fracture in the net section failure, analytical studies demonstrated that the current AISC specification formulation for addressing the influence of shear lag is unacceptable for cold-formed steel connections. Design equations were derived and are presented in the following discussion for assessing the influence of shear lag for both angles and channels.

DESIGN RECOMMENDATIONS

The First and Second Summary Reports present the experimental findings of the two-year research study. In addition to the discovery of new knowledge pertaining to the behavior of cold-formed steel bolted connections, this research effort was charged with recommending appropriate design guidelines. Although both summary reports contain suggested design solutions, subsequent studies were undertaken to formulate design recommendations that more closely parallel the commonly accepted design approaches of the AISC specifications.

The following design recommendations pertain to the bolt hole deformation of bearing connections and the shear lag effects for angles and channels.

Deformation of Bearing Connections. The generally accepted approach to defining a deformation limit in hot-rolled steel construction is given by the following:

$$P_n = 2.4dtF_u \qquad (1)$$

where,

d = nominal bolt diameter

t = base thickness of thinnest connected sheet

F_u = tensile strength of connected sheet.

Carril et al. (1994) presented the following design equation to define a deformation limit in cold-formed steel construction:

$$P_n = 1.93\ dtF_u \qquad (2)$$

Although Eqs. 1 and 2 are similar in format, they will create a dilemma for the designer. The AISI specifications prescribe that for material thicknesses greater 4.76 mm (3/16 in.), the AISC specification shall be used for design. Thus at 4.76 mm (3/16 in.), the above equations impose a discontinuity.

To alleviate the discontinuity created by Eqs. 1 and 2, subsequent study focused on the development of a transition from hot-rolled to cold-formed steel members. Carril et al. (1994) defined a constant c for each test specimen. The parameter c, as shown in Eq. 3, is the appropriate relationship that defines the deformation limit:

$$P_n = cdtF_u \qquad (3)$$

Figure 6 presents the relationship between c and the material thickness, t. A transition at 4.76 mm (3/16 in.) is achieved by adopting a linear relationship between c and t as defined by the following equation:

When t is in inches,

$$c = 4.64t + 1.53 \qquad (4)$$

When t is in mm,

$$c = 0.183t + 1.53 \qquad (5)$$

The above equations are valid when the distance along the line of force from the edge of the connected part to the center of the hole is greater than 1.5d, and the distance along the line of force between centers of holes is greater than 3.0d. The accuracy of Eqs. 4 and 5 is demonstrated by the relationship P'/P_n, where P' is the tested tensile load for a selected deformation limit of 6.35 mm (0.25 in.) (Carril et al., 1994). As summarized in Table 2, the mean and coefficient of variation for the tested assemblies is 1.023 and 0.097.

Applying the load and resistance factor design concepts for evaluating the strength reduction factor, ϕ, results in a ϕ of 0.70. Assuming a dead to live load ratio of 0.2, the corresponding allowable stress factor of safety is 1.61. However, recognizing the limited data available for this analysis, and to be consistent with the present AISI design specification, a smaller ϕ value of 0.65 and larger factor of safety of 2.22 are recommended.

Shear Lag Effects. The long standing relationship for recognizing the influence of shear lag on the tensile capacity of a bolted connection is a function of the distance from the shear plane to the center of gravity of the cross section, X, and the length of the connection, L. In hot-rolled construction, the detrimental influence of shear lag is accounted for by the following relationship:

$$U = 1 - X/L \qquad (5)$$

Figure 7 presents the relationship between the ratio of P_{ult}/P_n and X/L for the angle members reported in the Second Summary Report. P_{ult} is the tested tensile capacity of the section, and $P_n = A_n F_u$, is the computed tensile capacity. When computing A_n, the AISC definition for a bolt hole was assumed. That is, the bolt diameter is defined as 1.59 mm (1/16 in.) greater than the nominal hole diameter.

As shown by Fig. 7, the following relationship can be taken as an estimate of the degrading influence of shear lag on the tensile capacity of a bolted connection in an angle member:

$$U = 1 - 1.2(X/L) \le 0.9 \quad \ge 0.4 \qquad (6)$$

For the channel members considered in this study, Fig. 8 shows the relationship between P_{ult}/P_n and X/L. Following the format of Eq. 6, the following equation indicates the influence of shear lag on the tensile capacity of a bolted connection in a channel member:

$$U = 1 - 0.357\,(X/L) \le 0.9 \quad \ge 0.5 \qquad (7)$$

Staggered Bolt Holes. Based on a limited test program, Holcomb et al. (1995) determined that the use of the traditional AISC $s^2/4g$ to recognize the increased load capacity of a staggered bolt pattern was slightly unconservative. The test specimen geometry is given by Fig. 9. Table 4 summarizes the study results, and compares the test failure loads, P_t, to computed failure loads, P_n, using the P_t/P_n ratio. The ratios ranged from 0.808 to 0.949 with a mean value of 0.887.

The computed load capacity, P_n, was evaluated using the present AISI nominal tensile stress limit on the net section area, F_t. When determining the F_t, the definition of s, the spacing of the bolts was taken as the plate width divided by the number of bolts in the cross section under consideration (s = plate width/n_b). The net section area, A_n, however was defined as follows:

$$A_n = A_g - n_b d_h t + (\Sigma\, s^2/4g)t \qquad (8)$$

where

s = longitudinal center to center spacing of any two consecutive holes

g = transverse center to center spacing between fastener gage lines.

The low P_t/P_n ratios may be attributed to the lack of plastic flow that is available in a thin, flat sheet. The studies that serve as the basis for the $s^2/4g$ relationship are based on a yielding failure, not rupture of the plate (McGuire, 1968).

Another potential contributor to the poor performance of the test specimens maybe the small gage distance. The gage distance of approximately 1/2" did not conform to the minimum spacing of 3d (AISI, 1986). Thus, overlapping non-uniform stress distributions emanating from the bolt holes may have precipitated tearing of the sheet.

Insufficient information exists to formulate comprehensive design provisions for bolted connections having staggered hole patterns. To recognize the tensile capacity of staggered bolt configurations, a reduction factor, 0.90, may be applied to the computation of the nominal load capacity. The net area for design, therefore, would be given by the following:

$$A_n = 0.90(A_g - n_b d_h t + (\Sigma\, s^2/4g)t) \qquad (9)$$

where, n_b = number of bolts in the failure plane.
The nominal tension stress limit, F_t, is to be determined by the present AISI equations with the modification that the bolt spacing, s, be defined as the plate width divided by the number of bolts in the section being evaluated.

The use of Eq. 9 will create a discontinuity between the AISI and AISC specifications. However, because of the lack of test data necessary for a more exact design formulation, a discontinuity can not be avoided. The presence of a discontinuity should not be a significant design issue because the use of staggered hole patterns in cold-formed steel construction is not a common application.

SUMMARY

Based on the results of the recently completed UMR experimental investigation of bolted connections for flat sheets, and angles and channels cold-formed from flat sheet, the following significant findings were discovered and reported in two summary reports and this paper:

1. The deformation around a bolt resulting from bearing of the bolt on the sheet was found to be a function of the thickness of the connected sheets. An equation was derived that will enable the design engineer to account for deformation within a bolted connection.

2. Shear lag can have a degrading affect on the tensile capacity of a bolted connection. Equations were developed to estimate the effect of shear lag for both angle and channel members.

3. Staggered holes create a reduction in the efficiency of a flat sheet bolted connection. Based on a limited test program, a design recommendation is proposed that recognizes the inability of the sheet to achieve its full tensile strength.

ACKNOWLEDGEMENTS

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Table 1
Number of Flat Sheet Test Specimens

Failure Mode Type	Single Shear With Washers	Single Shear Without Washers	Double Shear With Washers	Double Shear Without Washers
III	66	10	189	142
II	26	7	-	-
II & III	39	6	-	-
I & II	23	12	69	39
I & III	9	-	28	20
II & V	16	10	-	2
I & II & III	6	-	-	-

Notes: Failure mode definitions (Yu 1991):
- Type I - Shearing parallel to direction of loading
- Type II - Bearing of bolt on the sheet
- Type III - Tearing of sheet perpendicular to the direction of loading
- Type IV - Shearing of the bolt
- Type V - Sheet tearing due to excessive bolt rotation and dishing of the sheet

Table 2
Material Properties

Thickness (in.)	F_y (ksi)	F_u	F_u/F_y (ksi)	Elongation %
0.040	35.80	55.84	1.56	50
0.070	32.06	52.47	1.64	50
0.120	36.61	53.02	1.45	44

Note: F_y and F_u values are the average of two tests
1 in. = 25.5 mm; 1 ksi = 6.9 MPa

Table 3
Comparison of Tested vs Computed Deformation Load Limit

Test Assembly	P'/P_n
AY22-1	1.108
AY22-2	1.137
AY23-1	1.131
AY23-3	1.211
BY13-1	1.192
BY13-2	1.022
BY13-3	0.939
AN32-1	1.092
AN32-2	1.200
AN33-1	1.123
AN33-2	1.071
BN33-1	0.962
BN33-2	0.965
DN12-2	0.894
DN12-3	0.979
DN22-1	1.053
DN22-2	1.011
AY12-1	1.148
AN12-2	1.046
BY12-1	1.015
BY12-2	0.955
BY12-3	0.997
BY22-1	0.985
BY22-2	0.998
BY22-3	1.113
BN32-1	1.070
BN32-2	1.065
DN32-1	1.012
DN32-2	1.014
EN12-1	0.883
EN12-2	0.864
EN22-1	0.910
EN22-2	0.907
EN32-1	0.892
EN32-2	0.863
Mean	1.023
COV	0.097

Table 4
Comparison of Tested to Computed Capacity
for Specimens with Staggered Holes

Test Assembly	Sheet Thickness (in.)	P_t (kips)	P_n (kips)	P_t/P_n
GN11-1	0.04	8.90	11.01	0.808
GN11-2	0.04	9.15	10.75	0.851
GN11-3	0.04	9.78	10.78	0.907
GN31-1	0.12	24.43	27.56	0.886
GN31-2	0.12	25.43	26.81	0.949
GN31-3	0.12	24.99	27.12	0.921
			Mean	0.887

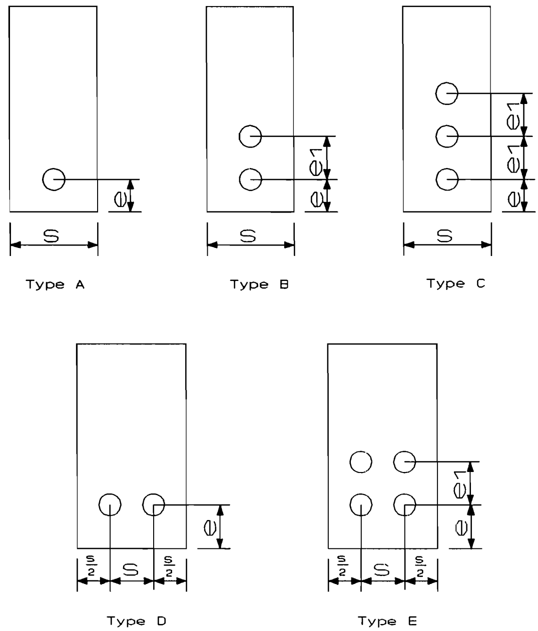

Fig. 1 Geometry of Test Specimens

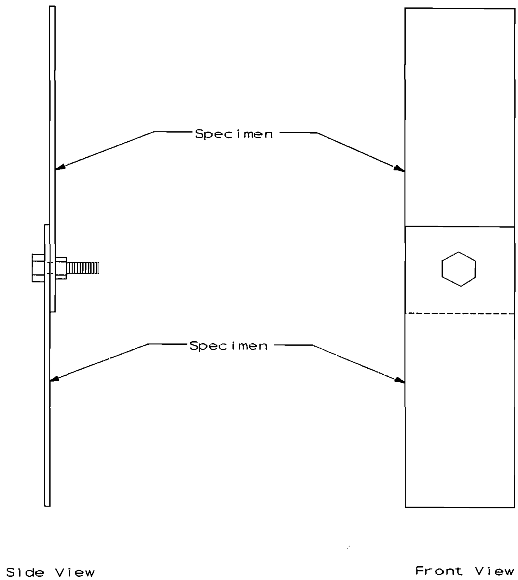

Fig. 2 Typical Test Assembly

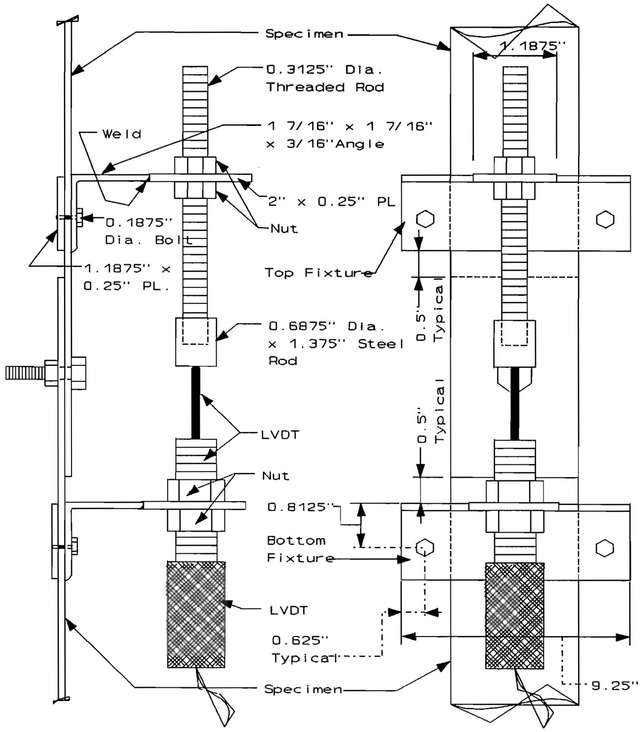

Fig. 3 LVDT Attachment of Test Assembly

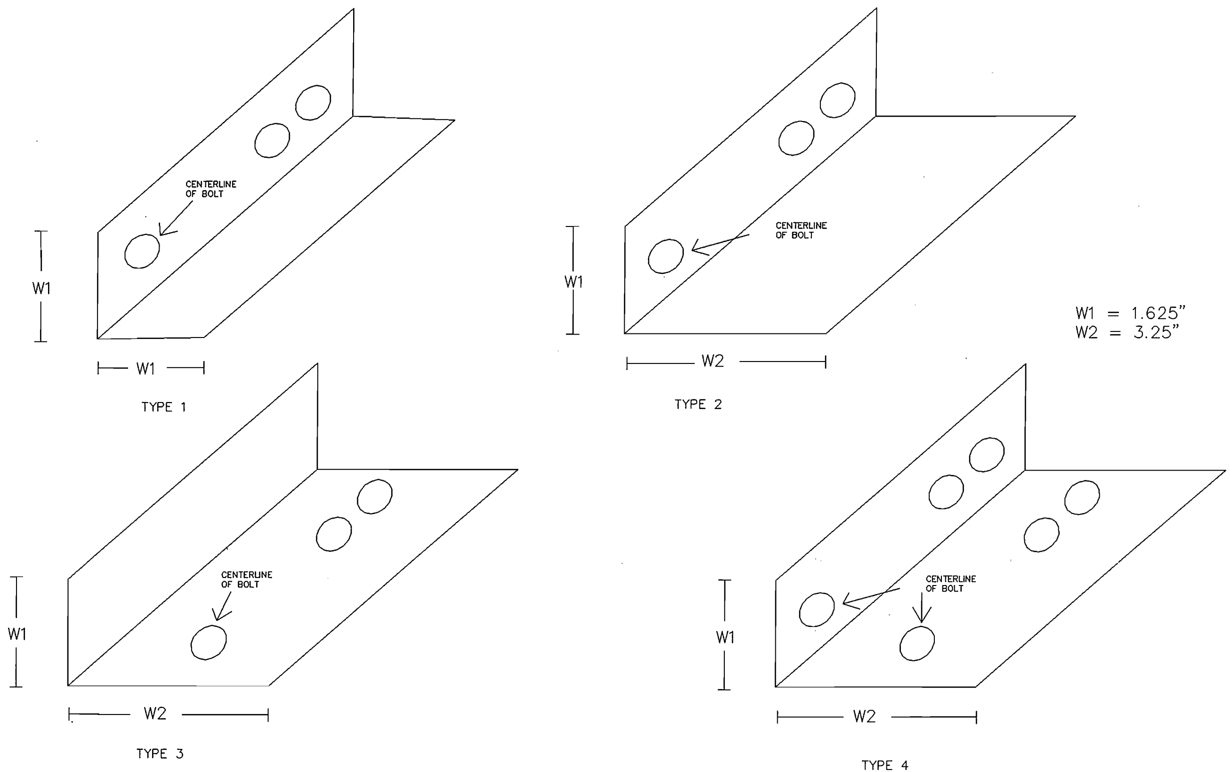

Fig. 4 Angle Test Specimens

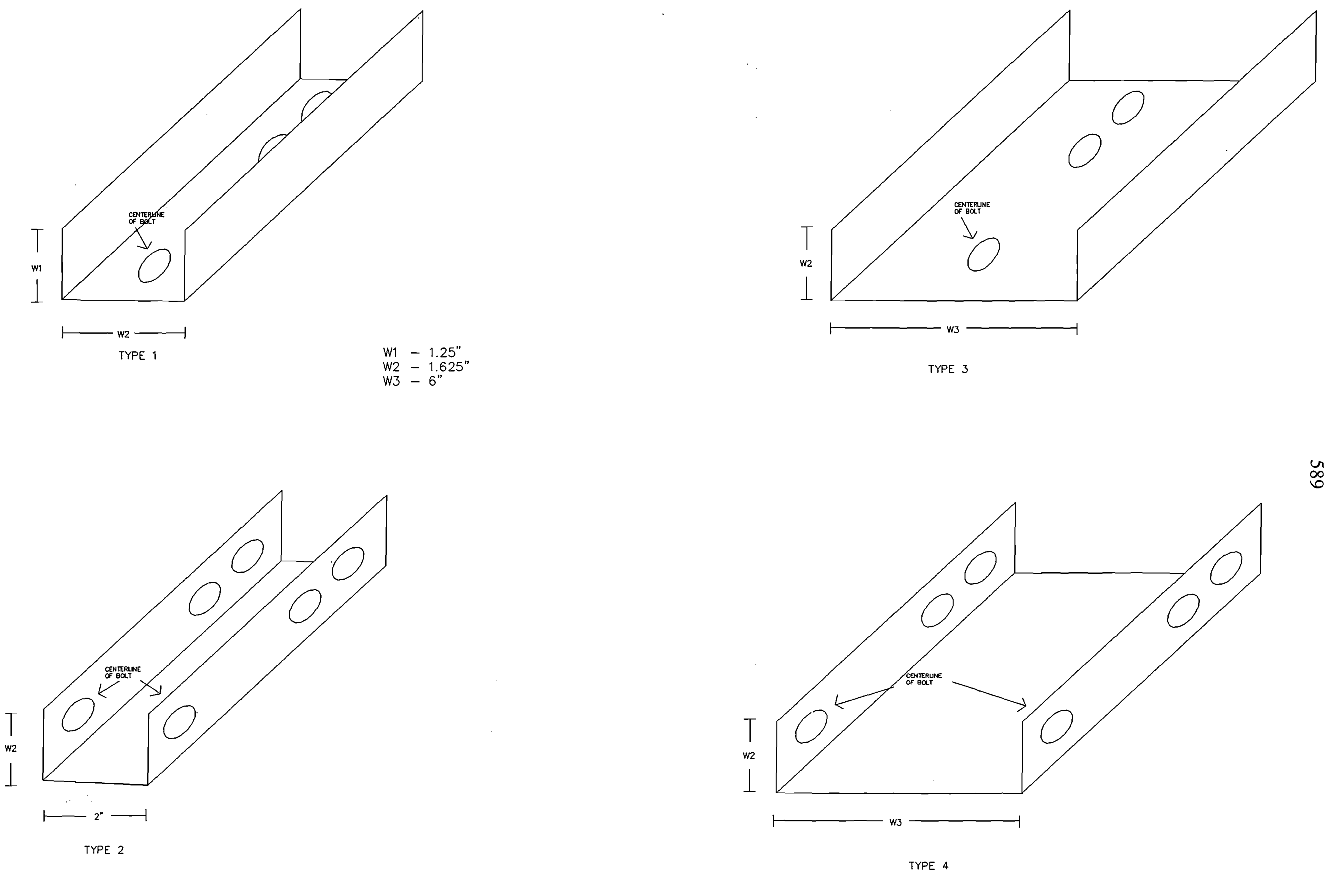

Fig. 5 Channel Test Specimens

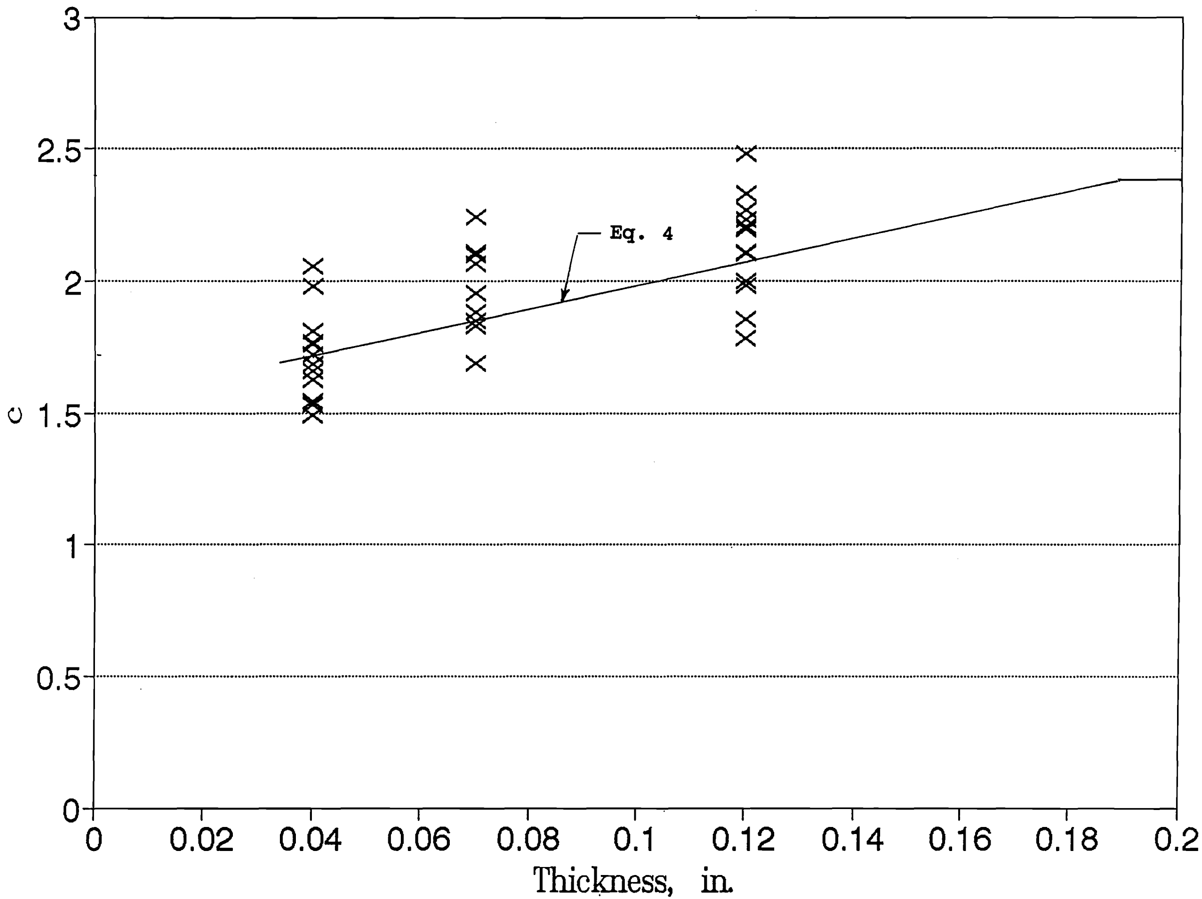

Fig. 6 Bearing Capacity Factor

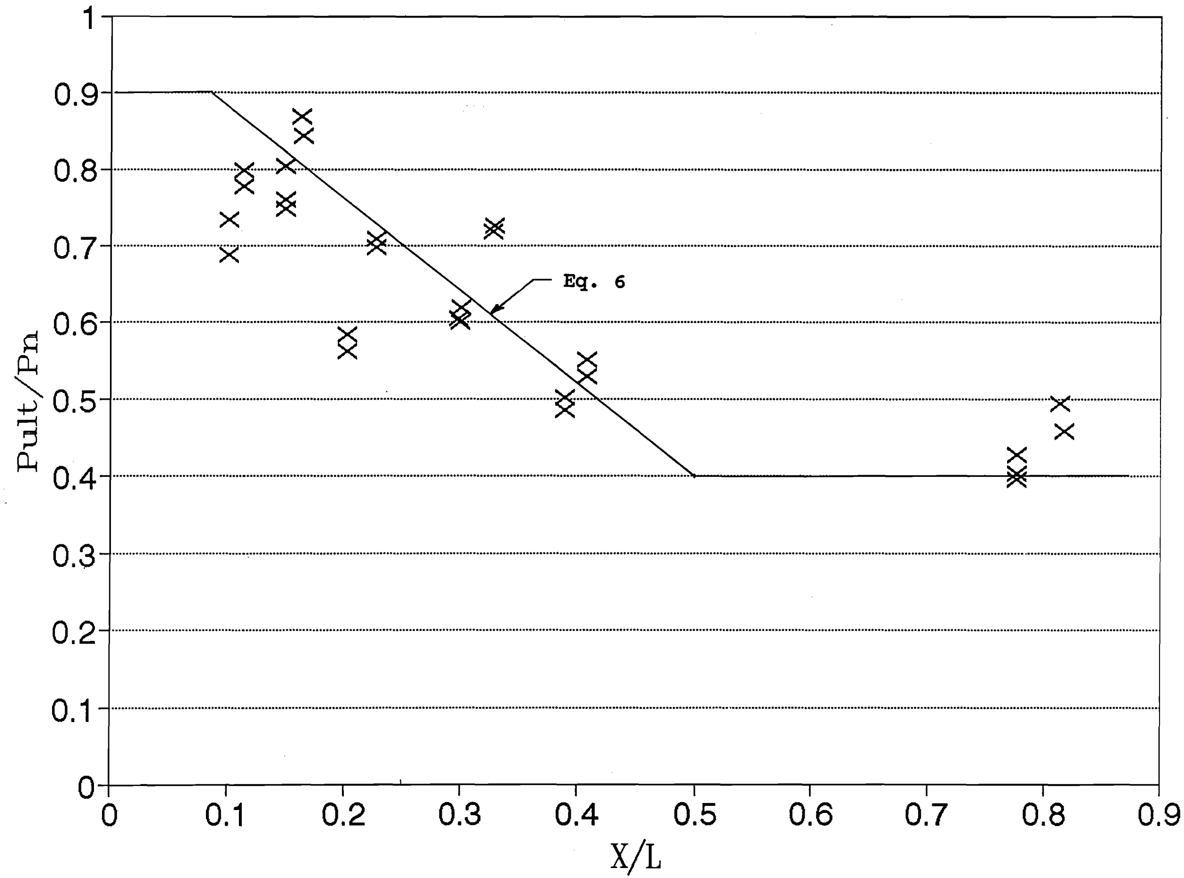

Fig. 7 Relationship Between X/L and Reduction in Member Strength Due to Shear Lag for Angle Sections

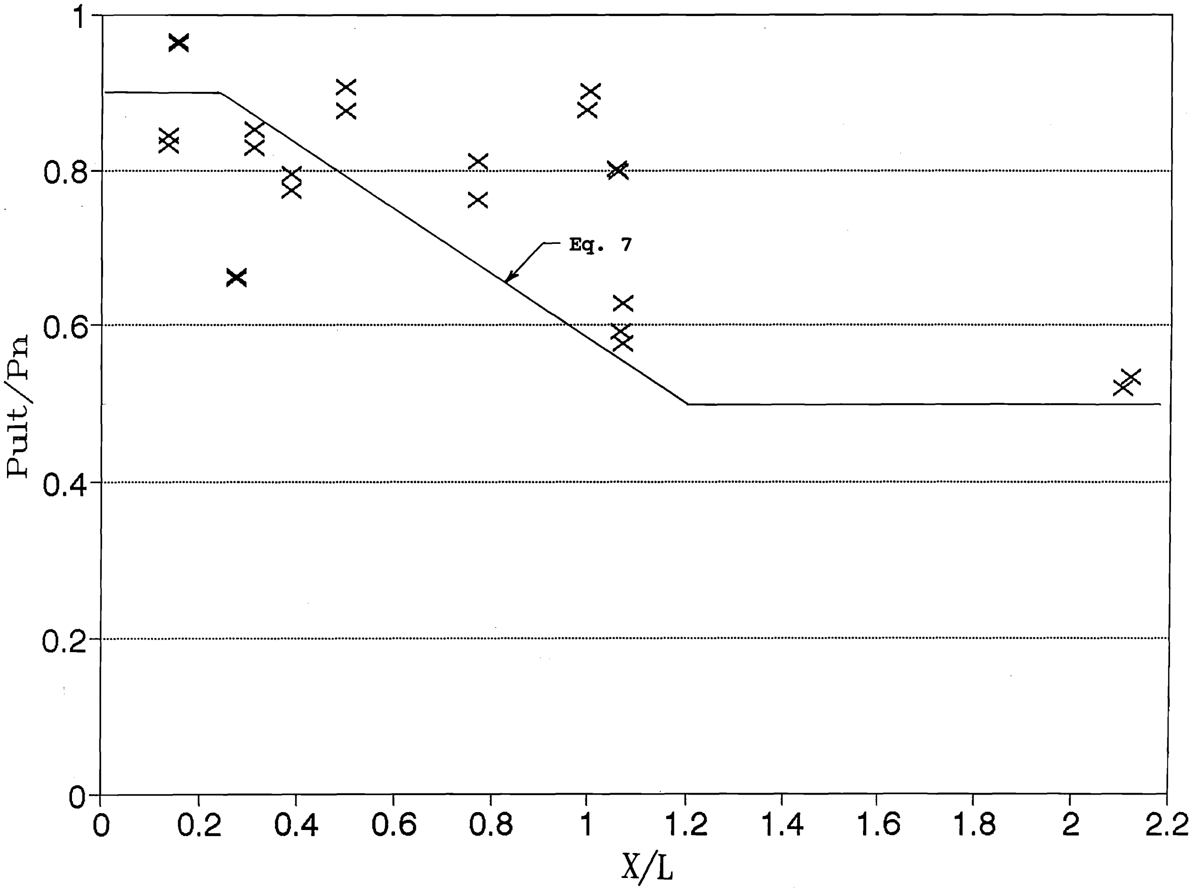

Fig. 8 Relationship Between X/L and Reduction in Member Strength Due to Shear Lag for Channel Sections

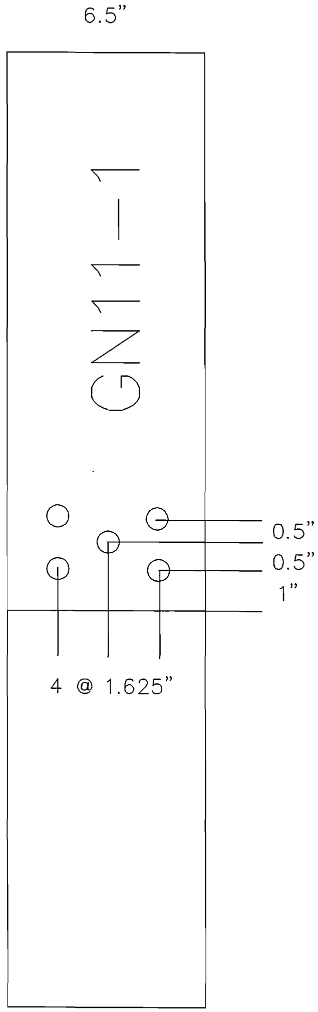

Fig. 9 Geometry of Staggered Hole Test Specimens